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Harold L. Brode

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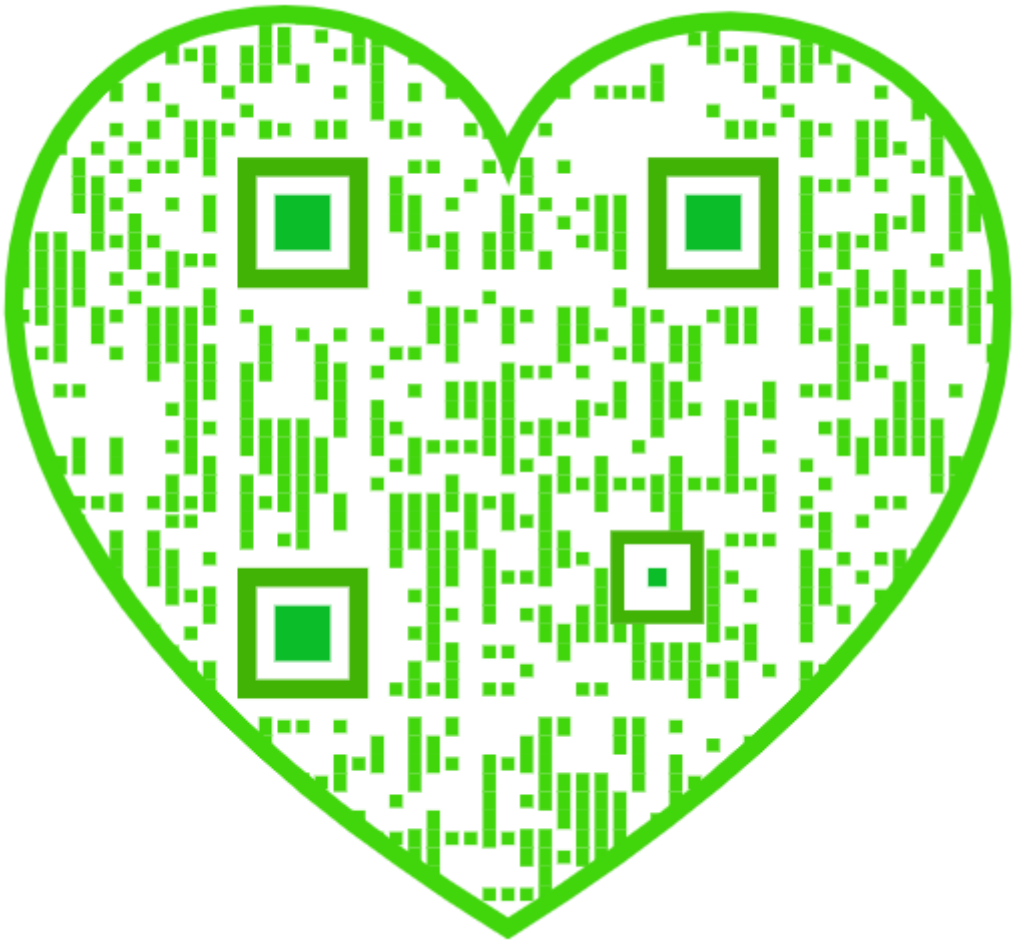

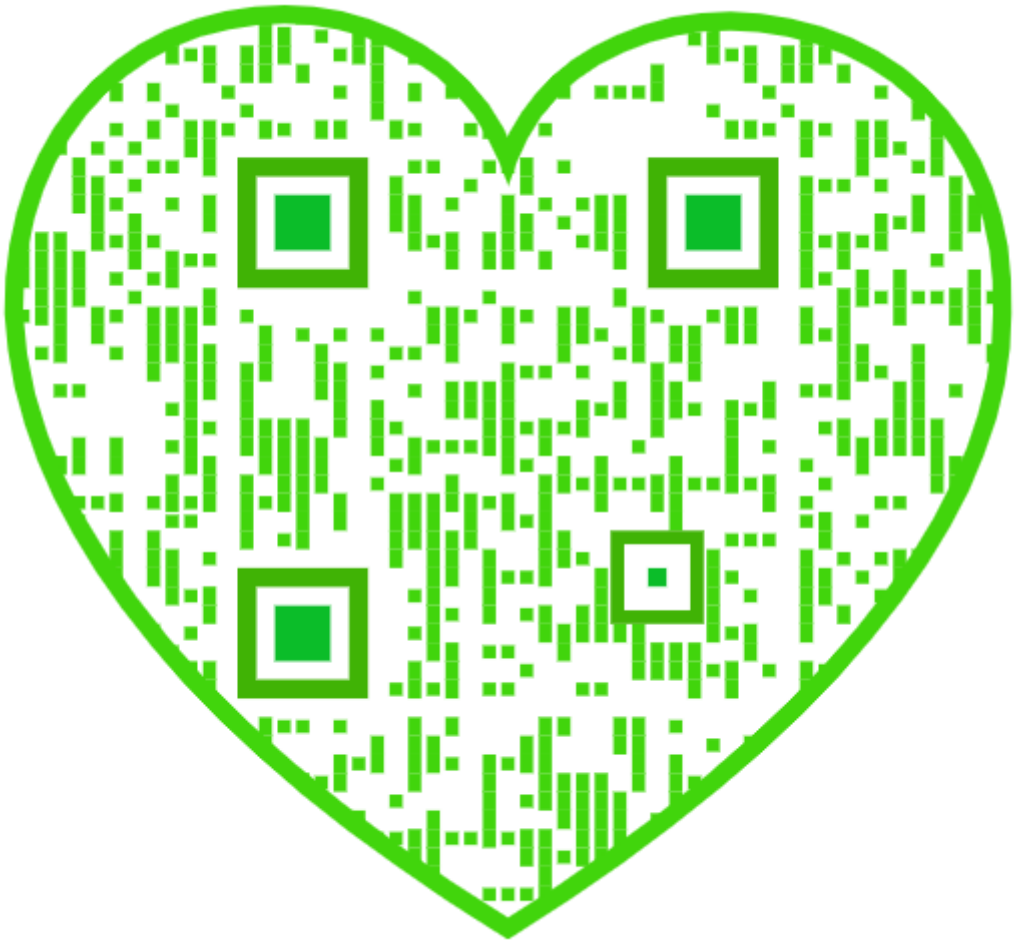

THERMAL RADIATION FROM NUCLEAR EXPLOSIONS

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ABSTRACT

A description of the explosion phenomena which determines the amount and character of the thermal radiation is presented together with the effects of atmospheric transmission and altitude of burst. The factors governing the response of materials to thermal radiation are outlined, and the nature and extent of large scale fires from nuclear explosions are discussed.

The extent of fires caused by the thermal radiation from nuclear explosions is determined by (1) the explosion characteristics, (2) the modifying influences of the atmosphere and transmission through it, and (3) the thermal absorption and combustion nature of the target materials.

THE EXPLOSION SOURCE

A megaton explosion creates some 10^{15} calories of heat in a few tons of bomb matter in a fraction of a microsecond. Such a high energy density leads to temperatures in the tens of millions of degrees and to a high rate of diffusion of the energy out of the bomb and through the surrounding air. This radiation transport or energy diffusion is initially faster than any hydrodynamic motions or shock wave speeds. Within a microsecond, most of the bomb's yield has flooded out of the still unexpanded but very hot bomb vapors into the air immediately around the burst point.

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The air is opaque to much of the bomb's early radiation until it has absorbed sufficient energy to rise to temperatures of nearly a million degrees itself. At such high temperatures air becomes completely ionized, all electrons being stripped from their various atomic nuclei. Such a plasma becomes relatively transparent to subsequent radiation - being incapable of much further radiation absorptions. The following flux of x-rays from the bomb experiences only Compton scattering in the hot air, and is absorbed only after it reaches the exterior cold air.

After a few microseconds, the radiation has diffused into a hot, high-pressure sphere of air several hundred feet in diameter. (Figure 1.) When the temperature drops much below a million degrees (centigrade), the rate of diffusion becomes slowed by the increasing opacity of the air as air ions recombine with their electrons. Eventually (in $\sim$ 100 μsecs), shock waves can form and expand the fireball further.

When the shock wave forms, it engulfs and heats more air. The shock-heated air is incandescent and radiates strongly, but, at the same time it is quite opaque thereby shielding or entraping the much higher temperatures in the interior radiation-heated regions. (Figure 2.) What one measures and what one sees in high-speed pictures of these early phases is a sphere whose radius equals that of the shock, radiating as a black body at the shock temperature, which is in fact the lowest temperature in the fireball at that early time. (The fireball of Figure 2 has this character of a glowing sphere - showing both the sharp shock appearance of a glassy ball and the blistered appearance caused by blobs of debris splashing against the back of the shock front.)

As this strong shock expands and weakens, it heats the engulfed air less and less. At a stage when the shock heating is no more than a few thousand degrees, the shock front begins to be transparent and we see through it to the hotter air behind. The shock, when it was stronger, raised this air to higher temperatures, and it is still at higher temperatures even though it has expanded some (Figure 3). Since the radiation rate is about proportional to the temperature to the fourth power, a sharp increase in the rate of emission occurs as the hot interior of the fireball shines through the no-longer opaque shock front.

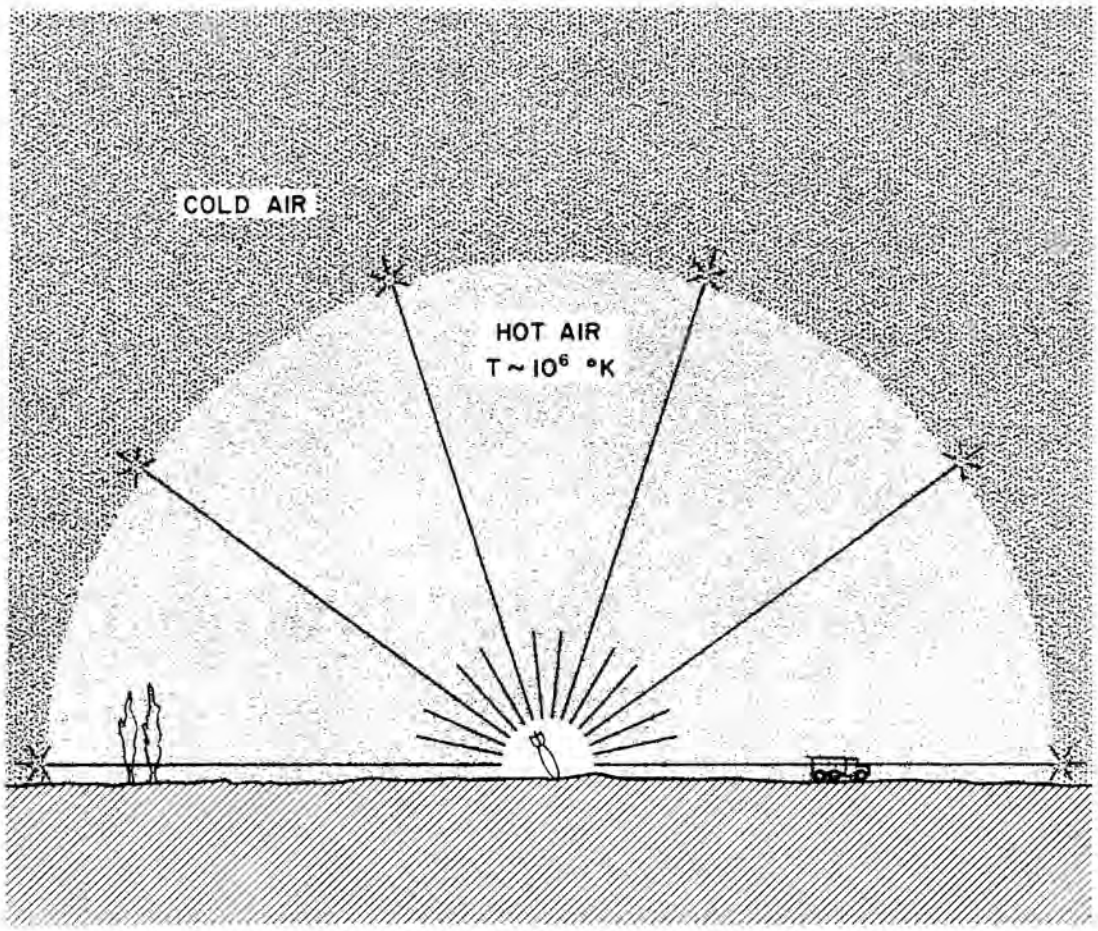


Fig.1---Early fireball growth by radiation transport

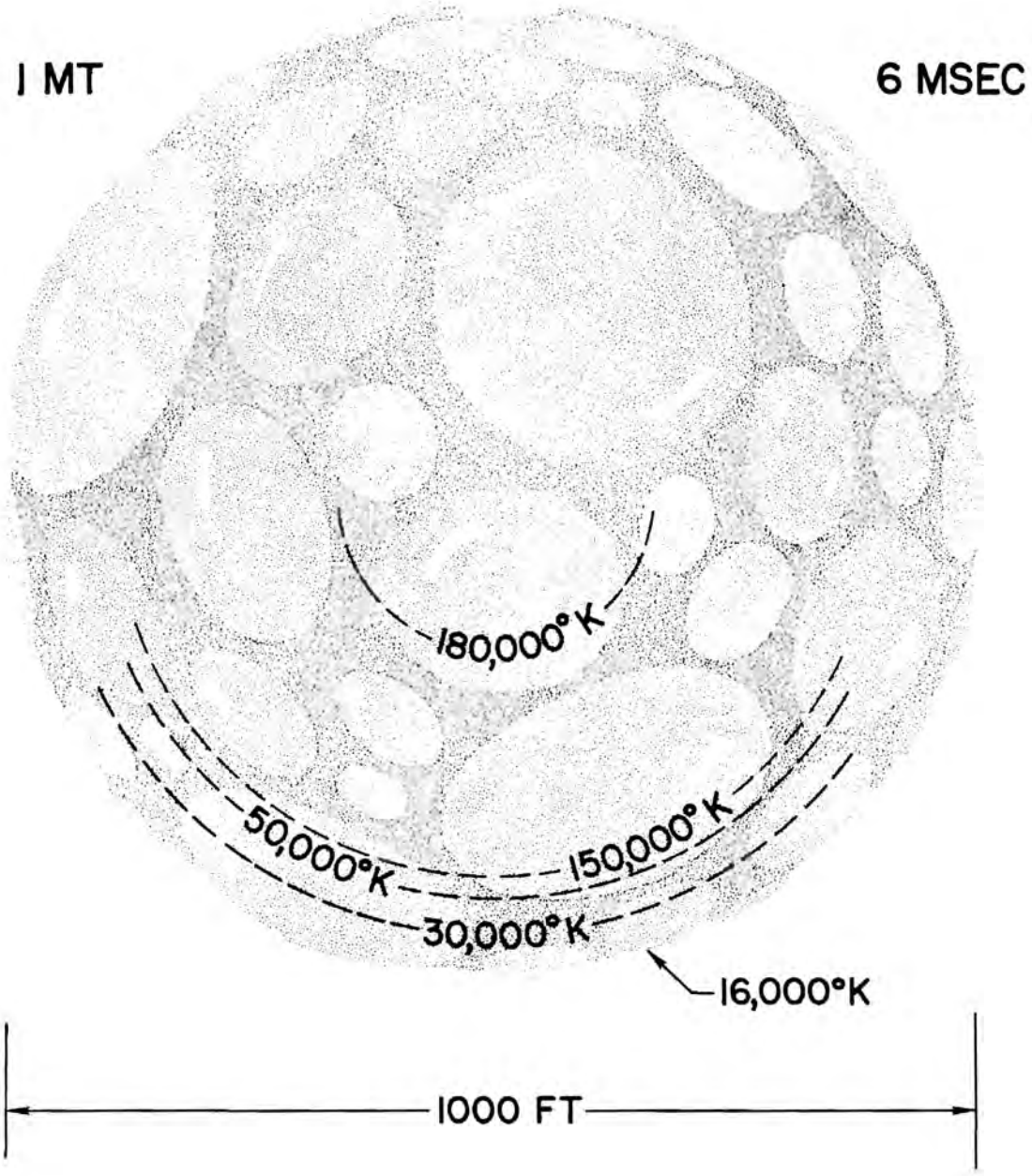


Fig.2---Early fireball size and temperature (while shock front is opaque)

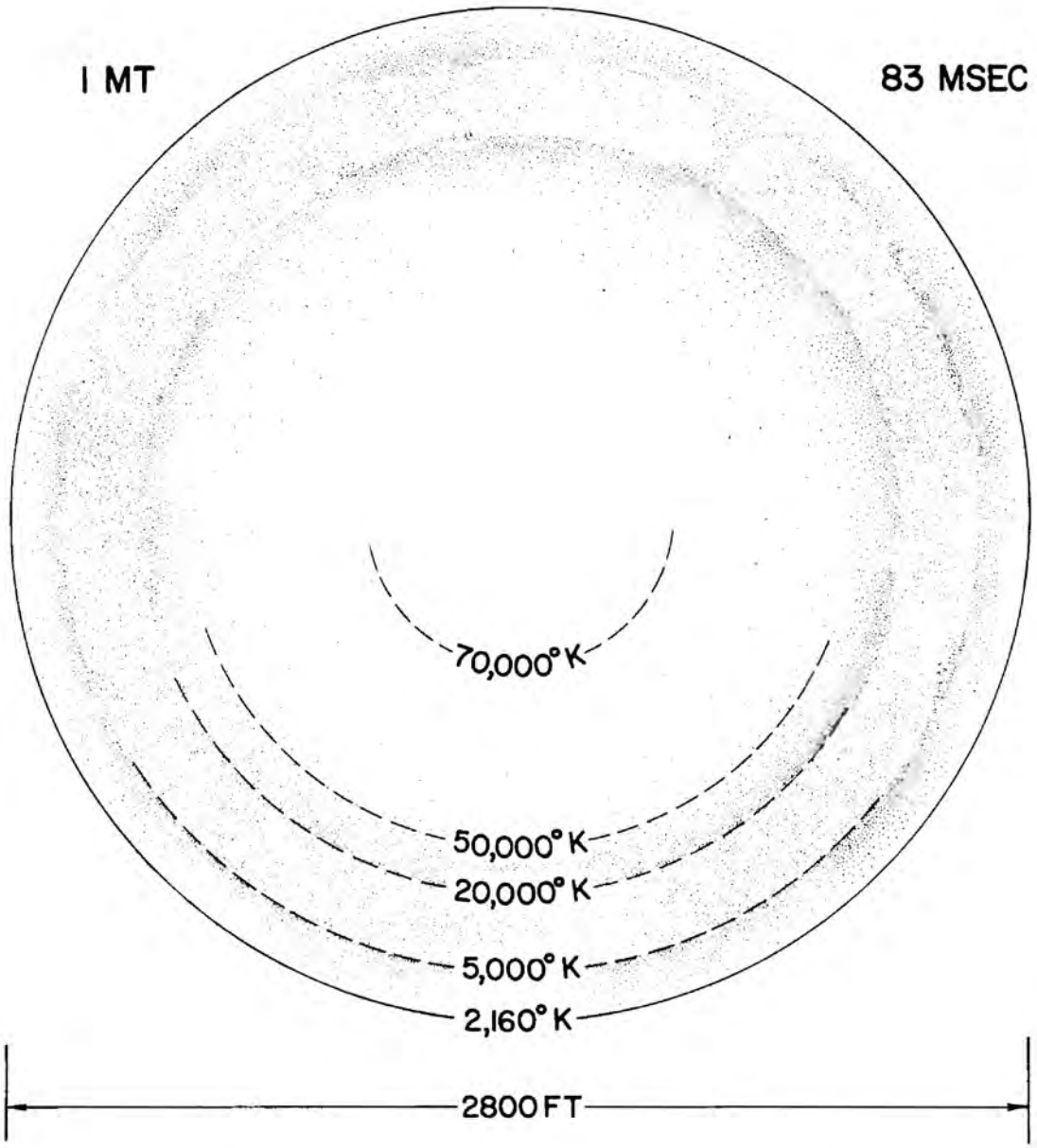


Fig.3---Fireball size and temperature at a time near minimum light intensity

Finally, the vast energies of the hot fireball begin to dissipate, and one can begin to see completely through it to the expanding bomb vapors (Figure 4). Only then does the rate of radiation decrease gradually to nothing as the remains of the fireball boil and rise through the atmosphere.

This sequence of optical and hydrodynamic events provides a thermal radiation pulse with two maxima and an intervening minimum (as in Figure 5). The first pulse follows the growth of the strong shock, decreasing in intensity as the shock front cools. The fact that the rate of radiation is proportional to the area of the radiating fireball surface (which grows with the speed of the shock) is less important than the fact that the shock front is radiating as a black body, hence its radiant flux decreases as the fourth power of its temperature (which in turn decreases rapidly with increasing shock radius).

When the shocked air becomes cold enough to be transparent, the radiant intensity rises again. The first pulse is so fast and comes from so small a radiant sphere that less than half of one per cent of the total energy of the explosion is radiated away before the time of minimum. The second pulse, however, lasts much longer and comes from a much larger effective radiating surface, and so accounts for the radiation of one third to one half of the total yield. Thus a large fraction of the explosion energy eventually escapes as radiant heat shining away to large distances. (It does not necessarily follow that the blast wave is proportionately less effective, since much of this thermal energy is lost too late and from too far behind the shock front to immediately reduce the shock effects.)

The surface of the earth interferes considerably with low or surface bursts so that less than half as much effective radiation as is expected from an air burst can be counted on from a contact or ground burst. As shown in Figure 6, the fireball is no longer a sphere and is partially obscured by the development of a precursor shock skirt of generally lower luminosity. Perhaps most significantly, its hot interior is thoroughly quenched by the sudden ingestion of vast amounts of cratered material. These megatons of evacuated dirt (for megaton yields) are injected at high velocity and have higher opacities and lower temperatures than

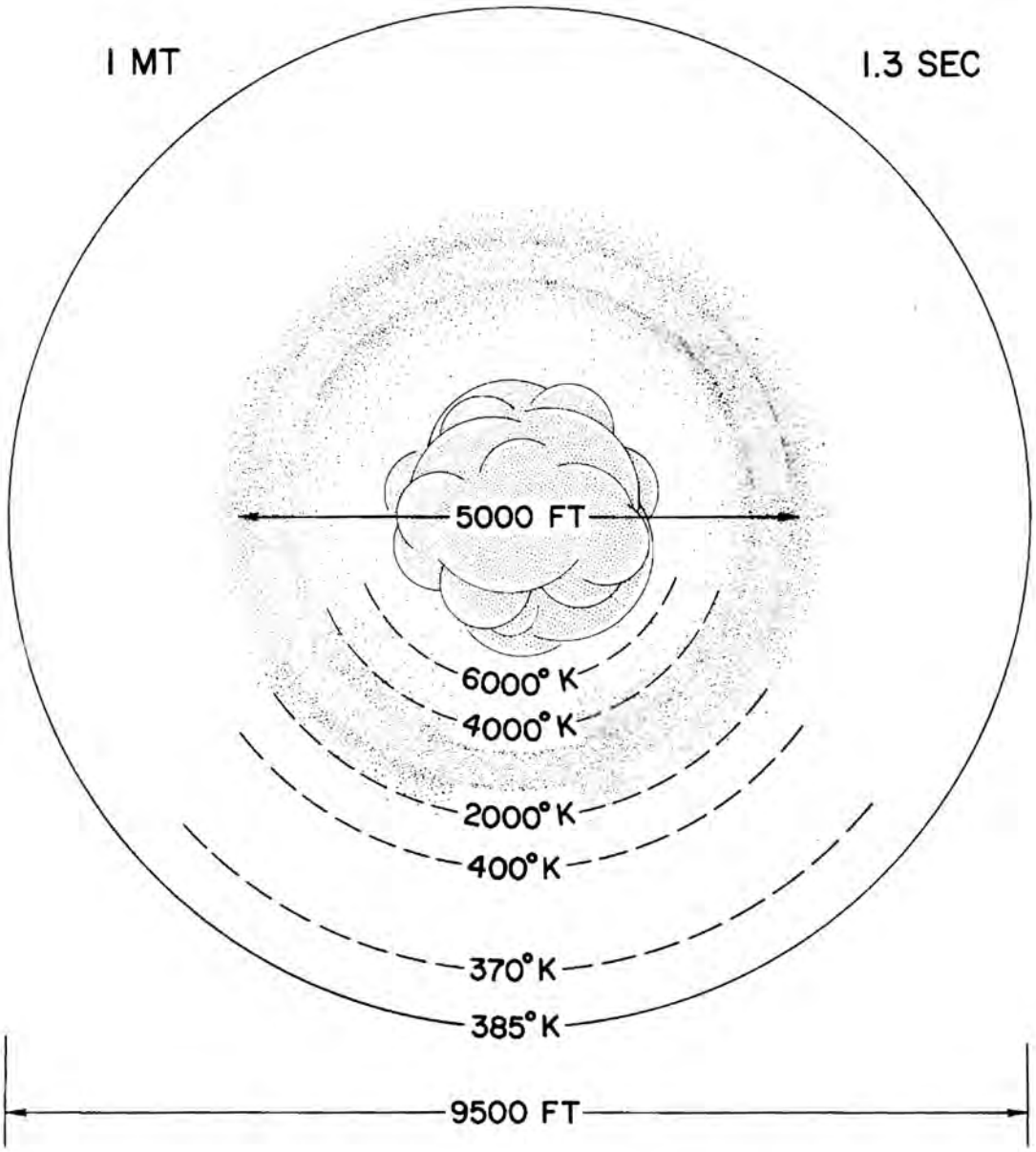


Fig.4---Late shock and fireball size and temperature

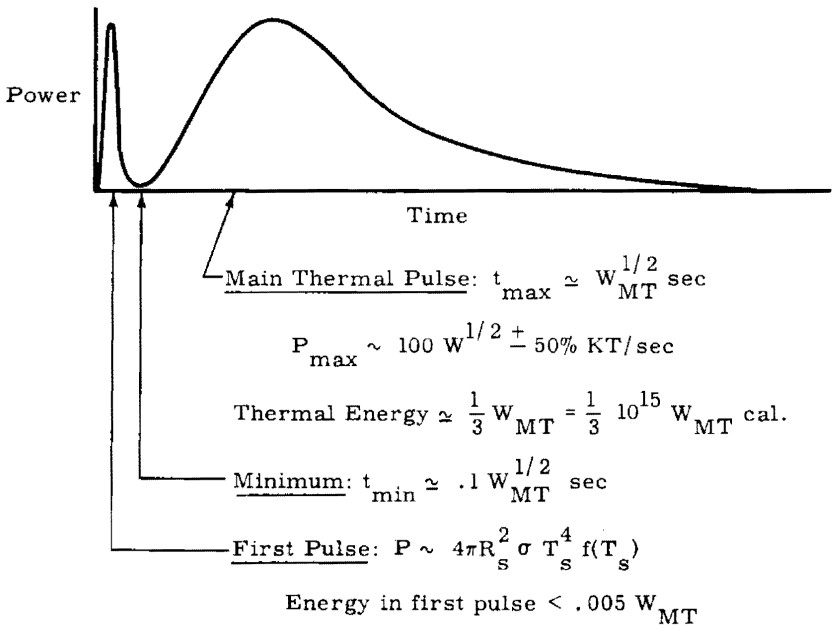

Power
Time
Main Thermal Pulse: $t_{max} \simeq W_{MT}^{1/2}$ sec
$P_{max} \sim 100\ W^{1/2} \pm 50\%$ KT/sec
Thermal Energy $\simeq \frac{1}{3} W_{MT} = \frac{1}{3}\ 10^{15}\ W_{MT}$ cal.
Minimum: $t_{min} \simeq .1\ W_{MT}^{1/2}$ sec
First Pulse: $P \sim 4\pi R_s^2 \sigma T_s^4 f(T_s)$
Energy in first pulse $< .005\ W_{MT}$

Fig.5---Thermal radiation rate versus time

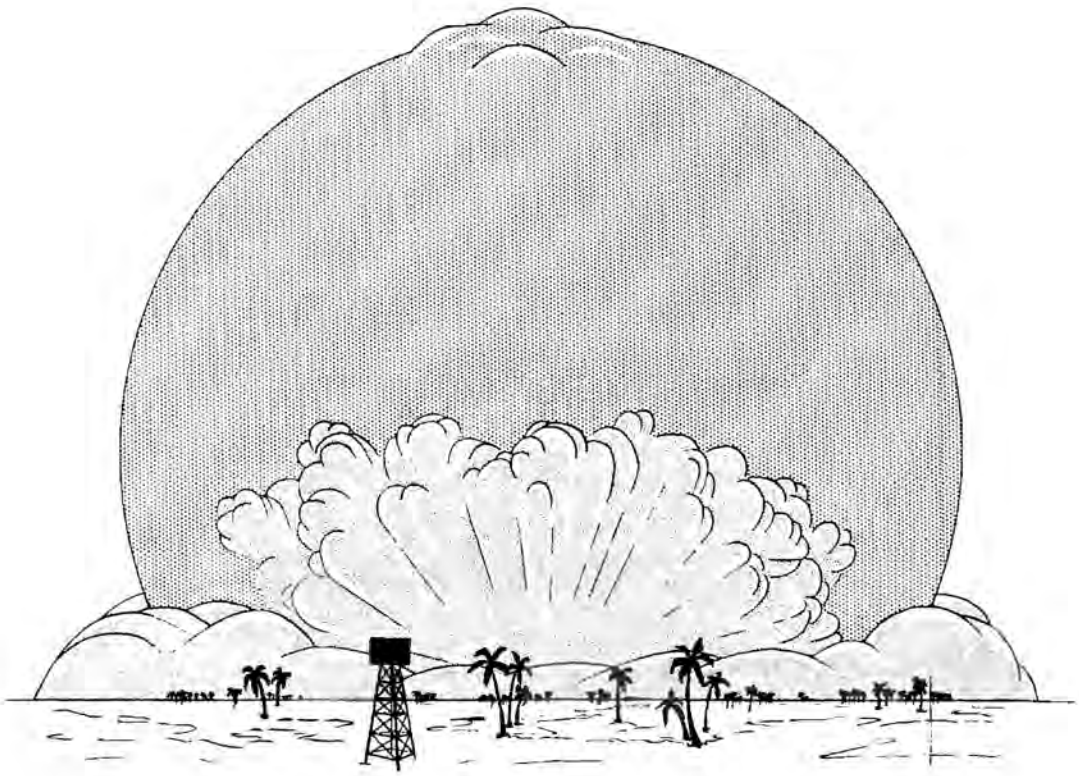


Fig.6---Surface burst features influencing thermal radiation

those of the fireball air. This debris does much to suppress the radiant efficiency of the fireball.

At late times, the turbulent mixing due to the instability of the hot fireball rising against gravity can play an important role in determining the rate at which the relatively opaque mixture of hot air and hot dirt is brought out to a radiating surface (Figure 7).

The spectral character and the timing and intensity of the thermal pulse change with increasing height of burst in the atmosphere. Where the sea level burst is generally typified by the double pulse at about one second and being over in about ten (for one megaton), at high altitudes the duration is more appropriately measured in milliseconds, and the minimum may begin to disappear altogether. Out at the edges of space, where there is insufficient air to trap the radiation, the burst is more like a great flashbulb with microsecond timing. Figure 8 illustrates this trend. The radiation is encouraged to escape more rapidly as the surrounding air is made less dense (and so less capable of energy absorption or of high opacity behavior).

ATMOSPHERIC EFFECTS

How the fireball develops and also what one observes at some distance away are both influenced by the optical properties of the air. To the distant observer, the ultraviolet and soft x-rays of the early intense fireball are well screened by the intervening air. The usual Planck radiant energy distribution with frequency (for black body radiation) is shown in Figure 9 to emphasize the obscuring effect of the normal atmosphere for the light from a very hot source. Since the air will pass freely only that fraction of the spectrum lying in the visible or infra-red (and so only that portion of the energy flux curves of Figure 9 that lie to the right of the ultraviolet region), the bulk of the radiant energy is not visible until a source has cooled to around $5000^{\circ}K$. That is, incidentally, about the effective surface temperature of the sun, and it is clear that if the sun's radiation spectrum were shifted to a slightly lower effective temperature, or if our atmosphere were slightly more opaque, our environment on earth, would be much different. It is largely this atmospheric

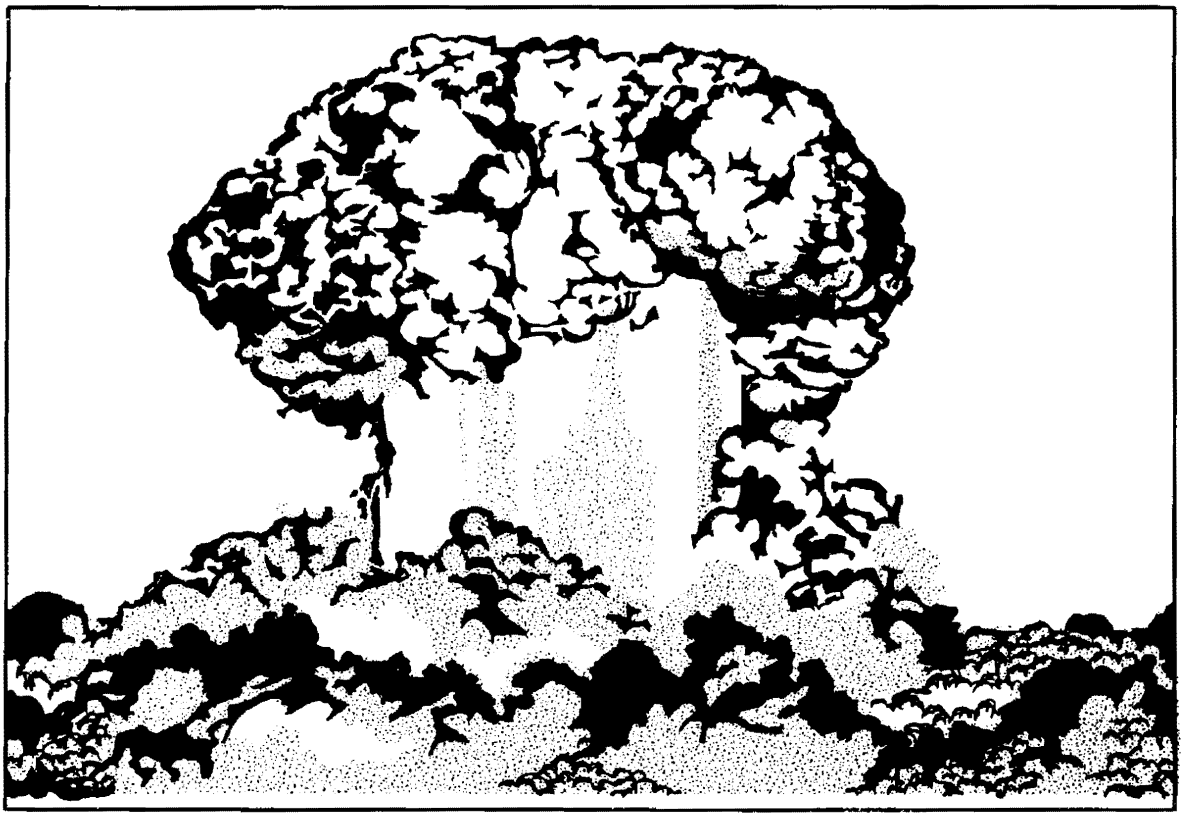


Fig.7---Turbulent mixing from late fireball or early cloud

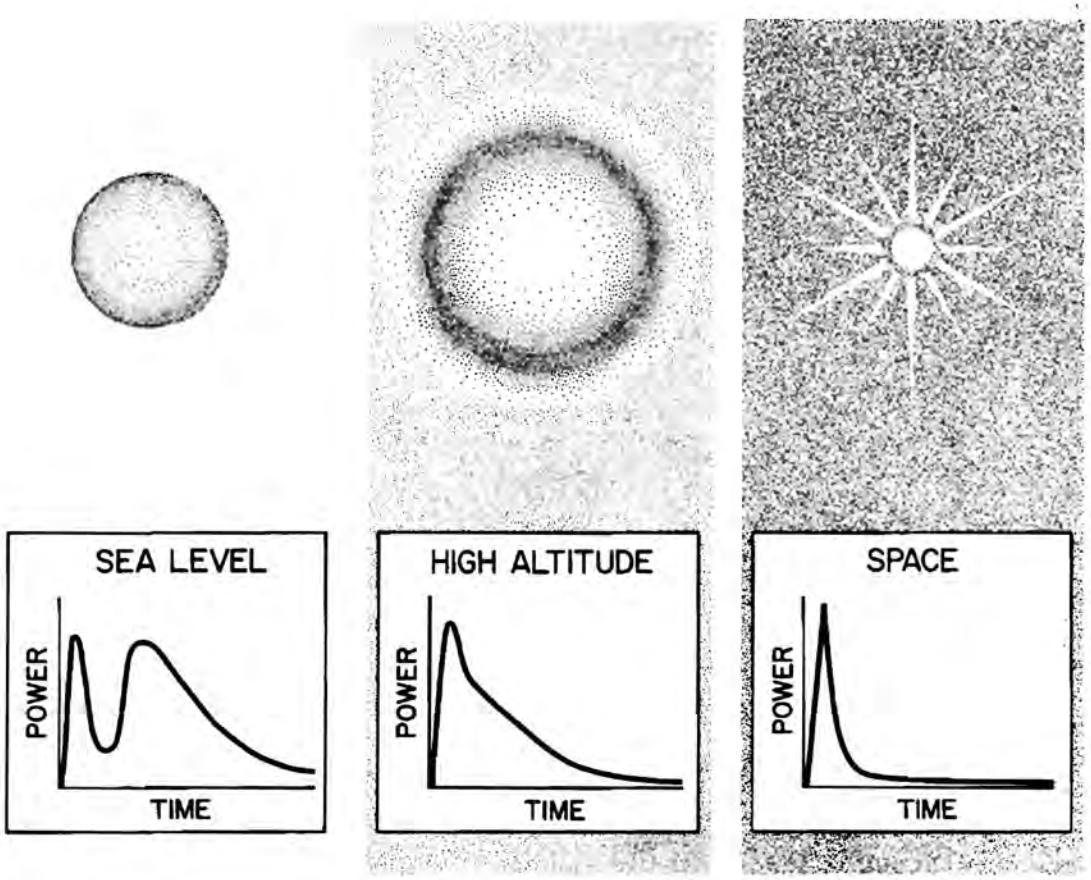


Fig.8---Altitude effect on thermal pulse

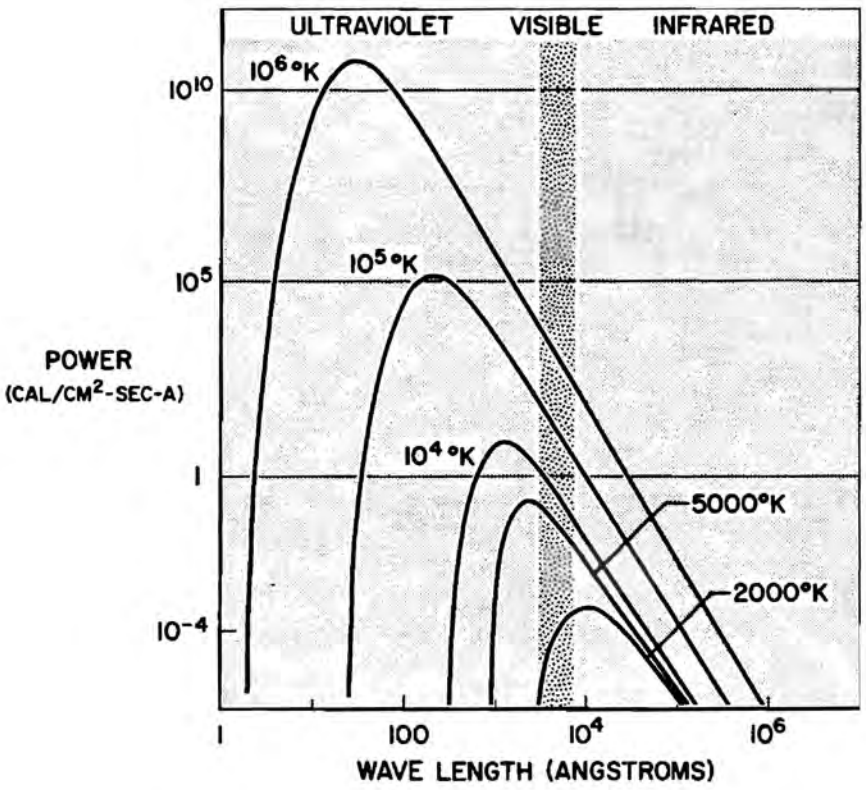


Fig.9---Planck (black body) radiation spectrum

cut-off of the high frequency part of a radiant source spectrum that postpones for a nuclear explosion the final power output until the nuclear explosion shock has well expanded.

Even in the visible light part of the radiation spectrum there is some scatter and absorption, and the bomb light is further reduced in a way expressible in terms of visibility. Coupling the approximate transmittance factors given in Figure 10 with the geometric decrease of total radiant intensity (incident energy per unit area) leads very approximately to

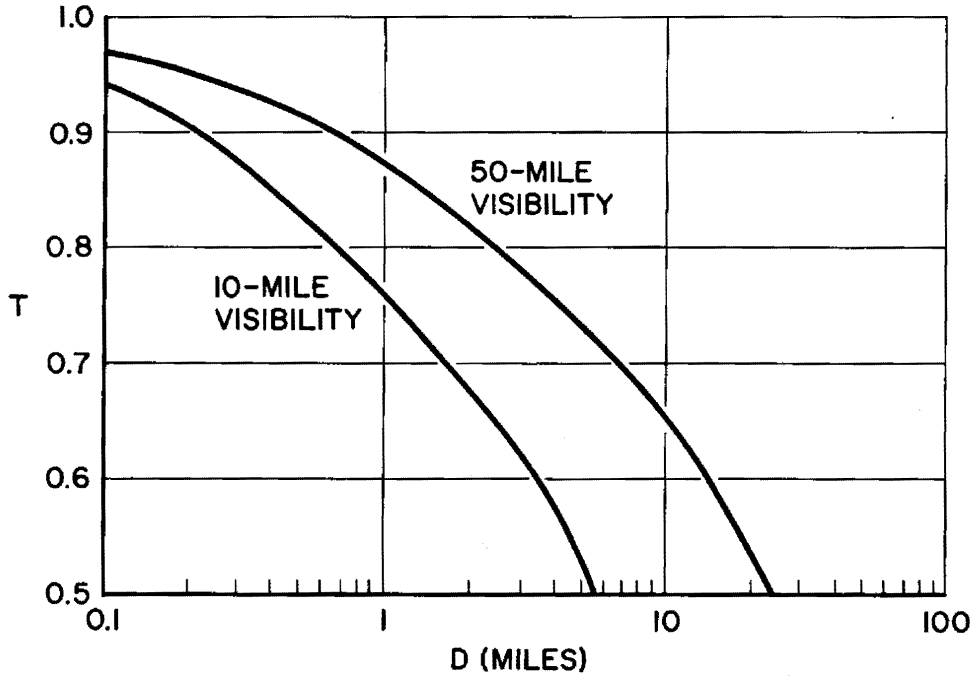
$$Q \simeq WT/D^2 \qquad \text{cal/cm}^2 ,$$

where W is the bomb yield in kilotons, T is the transmittance as suggested in Figure 10, and D is the distance from the burst point in miles. This expression indicates generally appropriate thermal loads from air bursts. The total amount from ground bursts is likely to be less than half of that from an air burst at the same yield and distance.

Thus, at about one mile from a one kiloton burst one expects less than one calorie per square centimeter (a not very serious heat load). At ten miles from 1 MT, however, the load could be as much as six calories/cm^2. The atmospheric attenuation becomes more important for the large distances (more of interest for large yields), while the attenuating and scattering effects are harder to estimate with useful accuracy.

EFFECTS ON MATERIALS

A few calories per square centimeter is sufficient to set some materials afire or to cause serious burns to exposed skin, but many factors influence the damaging effect of thermal radiation and most of these factors tend to limit or minimize the effectiveness. In discussing the character of the source it was noted that the significant features were the total energy, the time, the spectral history, and even the height of burst. If the radiation is delivered very slowly,



$Q(CAL/CM^2) \simeq W(KT)\ T/D^2(MI)$ AIR BURST

$\simeq$ ABOUT HALF AS MUCH FOR A SURFACE BURST

Fig.10---Transmittance and intensity versus distance

it is not effective. The desert sun, for example, puts out some two calories per square centimeter per minute, and although it is hot, it is not necessarily damaging. If the spectrum is too far in the infrared, then, no matter how long the radiation pours in, it may not be able to raise an exposed surface to a reacting temperature.
These source characteristics - the explosion yield, the time and spectral histories of the radiant flux, the fireball geometry and the height-of-burst effects - can have important influence on the response of exposed materials. Equally influential may be meteorological factors, and, perhaps more obviously, some properties of the materials themselves.

The absorption and diffusion through cloud layers or fog can be just as effective with the light from nuclear explosion as it is with sun light. Thermal energy getting through from a nuclear explosion above a cloud layer will be reduced by something like an order of magnitude. If a burst is beneath a cloud layer, the scattered radiation will be enhanced, but the direct beam (i.e., the unscattered radiation) is still likely to be the most damaging since it is not much altered by diffuse reflection from clouds. Smoke screens, fog - even industrial haze and smog - will be at least as effective as they now are in filtering sunlight, and perhaps more effective since most of the more distant exposures from bursts at or near the surface will be from radiation that must come through long stretches of the most polluted and opaque air near the earth's surface. Further, since much of the early energy comes in the ultraviolet, to which the air is relatively opaque, and since much of the high-yield, late-time radiation comes out in the infrared, to which the water-bearing lower atmosphere is fairly opaque, the effective transmittance may be lower than that for sunlight.

The properties of the exposed materials themselves may be the most significant factor in determining the response. Outside urban areas, the single most influential factor is likely to be the same condition of natural fuels that determine the extent of fire hazard from more common ignition sources. Everyone is aware of the sharp increase in fire danger when the countryside has had a dry spell. Forest conservationists customarily measure the fire danger level by the average moisture content in the forest fuel. When the moisture

content falls below twenty per cent, the hazard becomes worrisome; appreciably above that, the danger of spreading fires is much reduced.

We have all had the frustrating experience of trying to light a fire with green, moist, or wet wood. Just as wet wood can't be easily induced to burn, so thick combustibles are not easily ignited. Even a dry two-by-four burns reluctantly and stops burning when taken out of the fire. It is a different matter with a shingle or a bunch of kindling! Density also plays a role, a heavier combustible being harder to ignite than lighter-weight material. Of course, the chemistry of the material to the degree that it influences kindling temperatures and flammability, is an important parameter. Modern plastics tend to smoke and boil - to ablate but not to ignite in sustained burning - while paper trash burns readily. One feature which is more important under the thermal load than under most other fire sources is the color or reflectivity factor. Most people are aware of such effects; a dark shirt is much hotter under the sun than a light one. The burns corresponding to the dark patterns of the kimono of the Hiroshima woman dramatically illustrate the effect, as do the movies showing dark feathered gulls going down in flames before a Pacific test fireball while the lighter gulls fly away.

Just as most materials are not particularly sensitive to the sun's thermal radiation, and are not highly inflammable nor even ignitible, the surfaces exposed to the thermal intensity of a nuclear explosion are generally not given to sustained burning. Very intense heat loads may mar or melt surfaces, may char and burn surfaces while the heat is on, but may snuff out immediately afterward. Where the exposed materials meet all the favorable requirements, i.e., they are thin, of low density, dry, dark, and easily ignited (low kindling temperature), fires from exposure to thermal radiation will be most probable.

PRIMARY AND SECONDARY FIRES FROM NUCLEAR EXPLOSIONS

Although thermal radiation would start many fires in urban and in most suburban areas, such fires by themselves would seldom constitute a source of major destruction. Outside the region of extensive blast damage, fires in trash piles, in dry palm trunks, in roof shingles, in auto and household upholstery, drapes, or flammable stores are normally accessible and readily controllable. By the very fact that these fires start from material exposed to the incident light, they can be easily spotted and, in the absence of other distractions, can be quickly extinguished. Where the blast effects are severe and damage extensive, little effective fire fighting is likely. Growth and spreading of fires would be encouraged by the exposure of more flammable interiors of homes and by the rubble and kindling that the blast occasions.

Where there is blast damage, there is also the likelihood of secondary fires, i.e., fires caused by the disruption of electrical circuits, heaters and stoves, spilling of highly combustible gases or fluids on hot engines or pipes, or scattering of embers from open fires.

The extensive chemical explosive and fire bombing of World War II along with the Hiroshima and Nagasaki experience bear out the notion that serious fires generally start only in (and may in fact be restricted to) the region of extensive blast damage. In Hiroshima estimates of fire sources suggest that more than half the fires were from secondary or blast-generated sources; in Nagasaki, a greater fraction were traceable directly to thermal radiation.

LARGE SCALE FIRES - CONFLAGRATIONS AND FIRESTORMS

Most large fires are conflagrations, a burning wind-driven front encroaching on unburned fuels and leaving behind burned out char and ash. The thickness of the burning front depends on both the wind speed and the density and nature of the fuel. A grass fire has a front only a few feet thick and burns out so quickly that running directly through it may sometimes be safer than running away

from it. Although larger amounts of wood are used in house construction in the United States than in most other lands, the burning time of a single family residence is usually less than two hours. Such great conflagrations as the Chicago or San Francisco fires burned along such a front for days - shifting with the wind and available fuel - causing vast destruction but relatively little loss of life, and burning actively in a front seldom deeper than one or two blocks.

The fire bombing of World War II reached its peak in the great raids on Japanese cities. The huge Tokyo raid started extensive fires in about one third of the city, and the resulting conflagration burned over another third. In that instance, the casualties are quoted as being in excess of 200,000.

The firestorms of Hamburg and Dresden were of a different nature. A firestorm is more akin to a bonfire, and the conditions for it are those required for a bonfire. In a bonfire, the rising column of hot air sets up a draft which fans the fire, but at the same time contains it. If there is appreciable surface wind, then the rising column of hot air is swept off and the brisk up-draft is destroyed. A firestorm, like the bonfire must have reasonably still air, must have ample fuel, and must have a good start, i.e., the fuel must be burning all over at about the same time.

Hamburg and Dresden were first bombed with high explosives to break up buildings and then seeded with vast numbers of small fire bombs. These latter acted as many simultaneous sources of fire, setting ablaze whole areas all within a short time. A nuclear explosion can provide such fire sources far more effectively. Hiroshima suffered a firestorm from its nuclear attack.

But this nuclear super-match to light the fires cannot cause a firestorm where there is insufficient fuel or where the topography or weather interferes with the other bonfire requirements. Nagasaki did not develop a firestorm. The reason for this was probably the lower density of combustible materials in the extensive blast damage region at Nagasaki together with the partial obstruction provided by the surrounding hills. Further, the prevailing wind circulation in the valleys discouraged the development of a rising column of hot air

necessary to the firestorm type of fire.

Thus, the primary factors influencing large-scale fires can be identified as (1) the availability of fuel, (2) the density of the fuel, i.e., the extent of wood construction and the degree of built-upness, (3) the combustibility of the fuel, (4) the existence of fire-breaks (rivers, parks, lakes, broad avenues, freeways), and (5) target size; i.e., if nothing else can stop a spreading fire, then the limits of the urban area itself determine the coverage. Many other factors contribute to the nature and intensity of large scale fires, of course, but of these one may note as significant such matters as topography (as in San Francisco, Nagasaki, the Santa Monica Mountains - Bel Air fires), type and size of buildings (as in market, warehouse, or industrial area fires), nature and combustibility of contents or surrounding stored material, degree of isolation and insulation in construction.

Still one of the most important factors in any fire situation, aside from the existence of ample combustibles and the potentialities of nuclear explosives as fire igniters, is the meteorological influence - the weather. Recall again the consequent rise in fire hazard and the increased danger following weeks or even days of dry weather. The humidity need drop only for a day or two to make the Southern California hills potential tinderboxes. Elsewhere with higher levels of precipitation, the hazard is almost nonexistent, and during much of the time the possibility of fire spreading is negligible. During and shortly after rain or snowfall individual fires may burn, but they are not likely to spread rapidly beyond adjacent structures.

Although the thermal and blast effects from thermonuclear explosions are indeed capable of starting many fires in typical urban areas, the spreading and amalgamation of these fires and the possibilities for conflagrations or firestorms are matters not peculiar to nuclear war and are governed by the same factors which are of importance in more conventional conflagrations. Much of our long experience in preventing and fighting fires is applicable to the thermonuclear fire problem.

This background of disaster experience, however, can only partially prepare us for the sudden and widespread involvement in catastrophe from large scale nuclear attack. It is important to anticipate the consequences of the thorough disruption of all communication and normal avenues of transportation on the facilities for dealing with the many damaged and burning structures. Even a little preparation and training could be meaningful in reducing damage and loss of life following a nuclear explosion, but a very great deal of planning would be required to provide the most efficient rescue and fire fighting service possible in such mass chaos.

The forty thousand dead in Hamburg represented less than three per cent of the population. Undoubtedly, the extensive preparation and active fire fighting and rescue work in that city both reduced the casualties and prevented any significant further mortalities among the 40,000 wounded. Of the 80,000 killed in Hiroshima most died as a result of collapsing buildings, but many were trapped in rubble and were subsequently killed in the fire. No effective fire fighting and rescue operations were active that day. Although prompt outside aid kept the subsequent mortalities low amongst the nearly equal number of wounded, the Hiroshima dead represented some thirty per cent of the city's population.

It is significant that many are likely to survive the initial bombing effects even in the zones of "complete destruction." But of these survivors many will need aid or rescue or they will perish in the subsequent fires. Furthermore, much of material value remains after the blast but is threatened with destruction in the growing fires afterwards. Planning and preparation for effective lifesaving measures in time of such widespread disaster could well include provisions for fire control and rescue even in zones of extensive blast damage.

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